ANN-Based Modeling of Daily Global UV, PAR and Broadband Solar Radiant Fluxes in Cyprus

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Abstract In this study, Artificial Neural Network (ANN) techniques for estimating daily global UV, PAR and broadband solar radiant fluxes have been developed. The data used in this analysis are global ultraviolet UV (G_{UV}), global photosynthetic photon flux density (PAR-G_{PAR}), broadband global radiant flux (G), extraterrestrial radiant flux E_0, air temperature (T), relative humidity (Rh), sunshine duration (n), daylength (N), precipitable water (w) and O_3 column density. By using different combinations of the above variables as inputs, numerous ANN-models have been developed. For each model, the output is the daily global UV, PAR and broadband radiant fluxes. Firstly, a set of 2 $\times$ 365 points (2 years) has been used for training each network–model, whereas a set of 365 points (1 year) has been engaged for testing and validating the ANN-models. It has been found that ANN-models' accuracy depends on the parameters used as well as spectral range considered. Moreover, results obtained reveal that the ANN methodology is a promising tool for estimating both broadband and spectral radiant fluxes.

1 Introduction

The increasing global energy demands and the increasing fossil fuel prices stimulate countries to downsize energy consumption and exploit renewable energy sources. On the other hand, environmental problems caused by mass consumption of fossil energy (e.g. global warming) are also reason for concern. Reliable solar radiant flux measurements for estimating the dynamic behavior of solar energy

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systems' process and for simulating long-term operations are required. For thermal analysis performance through transient simulation algorithms, a crucial input is the solar radiant energy components incident on the collector surfaces. Nevertheless, direct measurements of solar radiant components at the site of interest are not available in many instances so only the use of either modeling simulations or empirically derived estimates can fill this gap (Lopez et al. 2001).

Further, plants require solar radiation for photosynthesis and their growth is proportional to the amount received, assuming that other environmental factors are not limiting. Specifically, the portion of solar spectrum utilized by plant biochemical processes in photosynthesis for converting light energy into biomass is a composite of wavelengths between 400 and 700 nm. These wavelength limits define the so-called photosynthetically active radiation-PAR (McCree 1972; Ross and Sulev 2000), covering both photon and energy terms.

On the other hand, the depletion in the concentration of ozone layer in the stratosphere may significantly increase the UV radiant flux reaching the earth's surface. These modifications have raised concern among scientists and policy makers during recent decades. This spectral UV component has deleterious effects in many biological systems: disrupts protein (DNA), causes skin cancer and eye cataracts in humans, losses of productivity and other destructing effects in plants (Parisi et al. 2007; Jacovides et al. 2009).

Bearing the above in mind, the purpose of this research is to establish ANN-models which making use of a limited number of widely available input variables, both radiometric and atmospheric, predict daily values of solar radiant components, namely broadband global, PAR and UV on a horizontal surface in Cyprus.

2 Data and Methodology

This analysis is based on hourly radiometric data collected at the semi-rural Athalassa site, Cyprus (35°15′N, 33°40′E, 165 m a.m.s.l.) for a 3-year period (2004–2006). Global (G) radiant flux (305–2,800 nm) was measured using the Kipp & Zonen model CM11 pyranometer (Delft, The Netherlands). The PAR (G_{PAR}) radiant flux (400–700 nm) was measured with a Licor quantum sensor LI-190SA (Lincoln, Nebraska, USA), while the UV (G_{UV}) radiant flux (280–380 nm) readings were obtained by adding Skye's sensors SKU-430 and 420 (Skye, Powys, UK) outputs. Daily values for all the radiometric components have been computed by summing the individual radiant fluxes over the course of a day.

Global radiant measurements have an estimated experimental error of about 3%, while spectral PAR data have an error less than 5% relative to measured values. The spectral UV data errors associated with the experimental data are conservatively estimated to be less than 9% (Jacovides et al. 2012). Air temperature (T), relative humidity (Rh), sunshine hours (n) and ozone column amount (O_3) are also available supplementing the radiometric data. It is noted that the ozone column amount has been extracted from the TOMS website (http://toms.gsfc.nasa.gov). Finally, the database was extended with the daily precipitable water content (w), air mass (m), and daylength (N). For the purpose of developing and testing the ANN-models, the whole database was divided into two subsets following a uniformly random distribution. The training data set contained 730 days and the test data set comprised 365 days.

3 Results

The computer codes for each ANN-model were developed in the MATLAB-software, whereas the architecture chosen is the feed-forward back propagation. All ANN-models used in this analysis are trained until the best performance is obtained. Once this criterion is achieved the optimal weights and biases are saved for further use to testing and validating the models. It also is noted here that in all ANN-models, one hidden layer was sufficient for modeling and estimating the daily global solar radiant fluxes (Tymvios et al. 2005; Benghanem et al. 2009).

Further, the performance of the ANN-models was assessed by means of the widely used statistical indicators, MBE and RMSE, which are normalized and they are expressed as a percentage of the corresponding mean values of the measured radiant fluxes. In addition, to indicate objectively whether the estimates of ANN-models are statistically significant, a supplementary statistical indicator, the *t-test*, combining both MBE and RMSE in their original form, is used (Jacovides and Kontogianis 1995).

Figure 1 displays predicted global radiant flux values through ANN-4 (Fig. 1a) and ANN-5 (Fig. 1b) models versus measured values. Figure 1c shows statistics of all ANN-models' developed here; this figure clearly indicates that ANN-4 and ANN-5 models provide the lower MBE and RMSE, while ANN-3, ANN-2 and ANN-1 models follow in that order. Results obtained through the five ANN-models developed here are statistically significant at the particular confidence level 97.5%, since their *t-test* values are less than the critical one ($t_{crit} = 1.96$).

Figure 2 displays a comparison between measured and predicted daily global G_{PAR} radiant flux obtained through ANN-4 model employing simple variables (Fig. 2a) and ANN-3 model using both solar and atmospheric variables (Fig. 2b), whereas statistics of the eight ANN-models developed are given in Fig. 2c. From these figures an acceptable agreement between measured and predicted daily global PAR radiant flux is obtained through all ANN-models. That is, all ANN-models' predictions are statistically significant at the particular confidence level 97.5%.

Viewing further ANN-models' statistics it is clear that the simple ANN's model making use of sunshine, daylength and precipitable water as inputs variables predicts accurately the daily global radiant flux, while the ANN-3 performed best when comparing against all ANN-models developed here. Earlier studies showed that G_{PAR} is strongly correlated with G (Ge et al. 2011) further implying the crucial role of the global radiant flux in modeling spectral radiant fluxes (Tymvios et al. 2008; Jacovides et al. 2009).

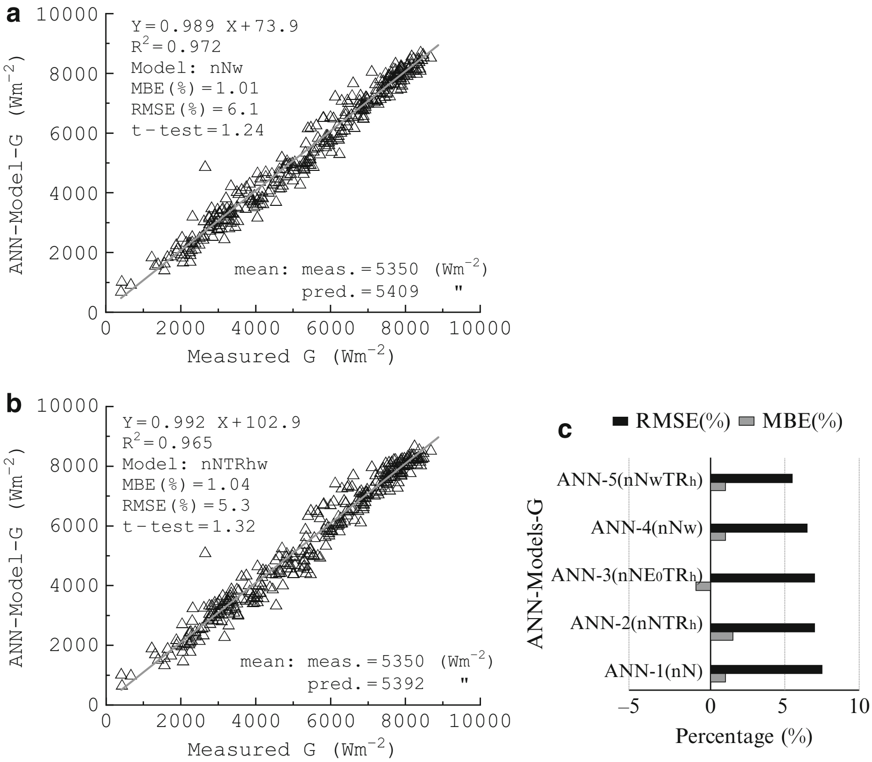

Fig. 1 ANN-4 (**a**) and ANN-5 (**b**) models' predictions for G radiant flux along with all ANN-models' statistics (**c**)

Further, Fig. 3 displays selected examples of scatter plots between ANN-3 (Fig. 3a) and ANN-4 models versus measured UV radiant flux, while ANN-models' statistics are given in Fig. 3c. It is well known that UV radiant flux is affected by cloudiness, optical air mass and ozone column amount (Junk et al. 2007; Bilbao et al. 2010), whereas numerous studies reported on the effective correlation between global G radiant flux and G_{UV} (Foyo-Moreno et al. 2003; Alados et al. 2004; Jacovides et al. 2009).

Further comparison between the two ANN-models given in Fig. 3a, b reveals that effective predictors affecting the ultraviolet solar portion may be included in modeling UV studies. It is clear that all statistical indicators MBE(%), RMSE(%) and *t-test* have been substantially improved when predictors, namely n, N, m, G, O_3 T and Rh are included in the ANN-model, further verifying earlier findings reported by various workers (i.e. Barbero et al. 2006; Junk et al. 2007).

Moreover, it is underlined here that RMSE and MBE values obtained through all ANN-models are consistent with those reported by other researchers for the UV radiant flux. Thus, Alados et al. (2004) reported RMSE (%) values ranging between

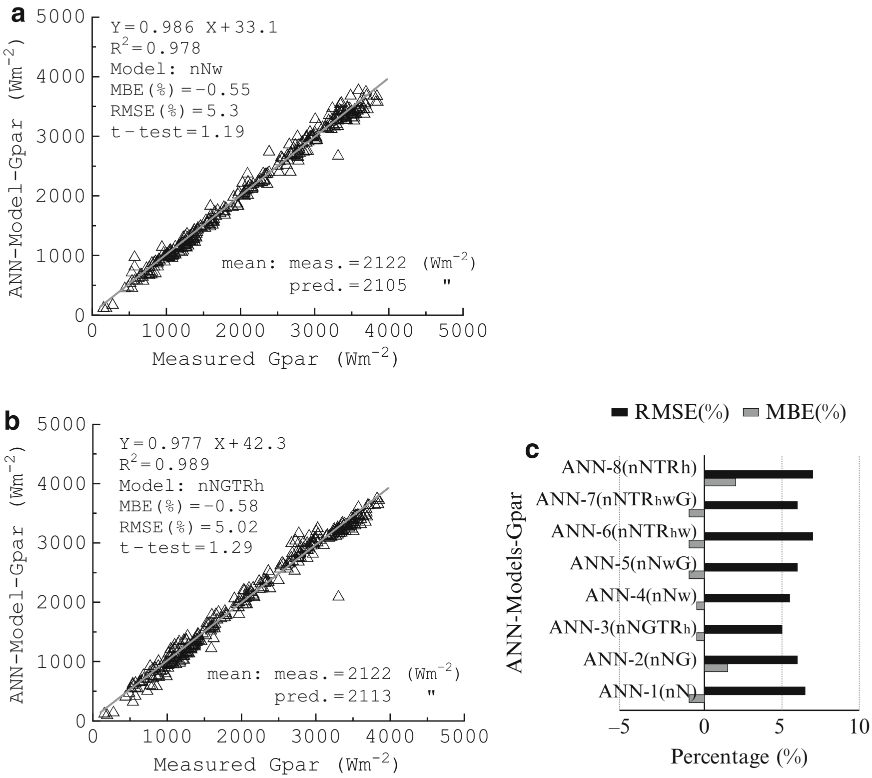

Fig. 2 ANN-4 (**a**) and ANN-3 (**b**) models' results for G_{PAR} radiant flux along with all ANN-models' statistics(**c**)

14.4% and 20.9% with relevant ANN-models applied for the Spanish environment. In contrast, MBE values reported for Spain are much less than that found here, whereas the present ANN-3, 4-models' results seem to be exceptions.

Further commenting on the ANN-models' performance, it is clear that the simplest ANN-model used as inputs n and N. Results on RMSE and MBE reveal that for both G and G_{PAR}, this combination is sufficient in producing acceptable radiant fluxes values; by contrast, this combination is not true for G_{UV}. Interestingly, by adding O_3 amount the simple ANN-model substantially improved, further revealing that ozone amount may be taken into account for modeling UV studies. The important role of O_3 on ANN's predictions is further demonstrated through ANN-6 versus ANN-5 comparison. That is, in ANN-6 model n, N and m are the inputs with RMSE and MBE of about 14% and −3.5% respectively; while in ANN-5 model by adding O_3 amount model's predictions are improved, with RMSE ~ 12.4% and MBE ~ −1.05%. It also is clear that ANN-4 model's performance is the best since numerous effective parameters, both solar and atmospheric, are included.

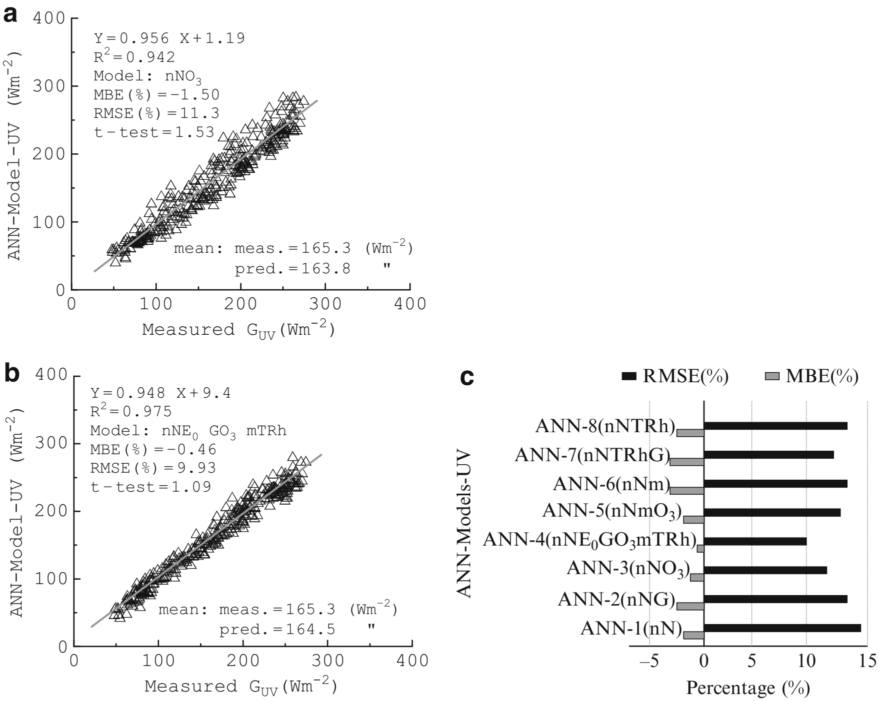

Fig. 3 ANN-3 (**a**) and ANN-4 (**b**) models results for G_{UV} radiant flux along with all ANN-models' statistics (**c**)

In principle, as reported by numerous researchers worldwide, most of the parameters likely affecting radiant components (ozone, cloudiness, trace gases, dust aerosols, site's characteristics, ground albedo, geometrical factors, etc.) may result in dissimilar variability on spectral PAR and UV modeling tools. Nevertheless, these parameters could have simultaneous changes which may add up resulting in spectral fluxes changes up to 30% or even more. On the other hand, several other parameters may inversely impact on the spectral radiant fluxes changes so that the net result may have an opposite sign compared to the above one, further reflecting the models' predictions. Therefore, for modeling accuracy of the spectral radiant fluxes it is essential to have as many measurements as possible of these radiant fluxes under diverse environmental conditions.

4 Conclusions

Design and analysis of artificial neural network models based on multilayer perceptron for the estimation of daily solar radiant components reveal the feasibility of this tool for predicting G, G_{PAR} and G_{UV} radiant fluxes. In this study case only one hidden layer is sufficient for estimating daily global spectral radiant fluxes through both solar and atmospheric parameters. Sunshine duration plays an important role in obtaining accurate results, whereas other parameters used may have conflicting influences on the ANN-models' predictions. Comparing statistical performances for all ANN-models' presented in this analysis, it can be seen that the models ANN-(nNTRhw) for G, ANN-(nNGTRh) for G_{PAR} and ANN-(nNE_0GO_3m TR_h) for G_{UV} exhibit the best results. Moreover, results obtained in this study render the ANN methodology as a promising alternative for estimating both broadband and spectral radiant fluxes.

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